Quantifying California's Greenhouse Emissions with Atmospheric Inverse Approaches: The CALGEM Project

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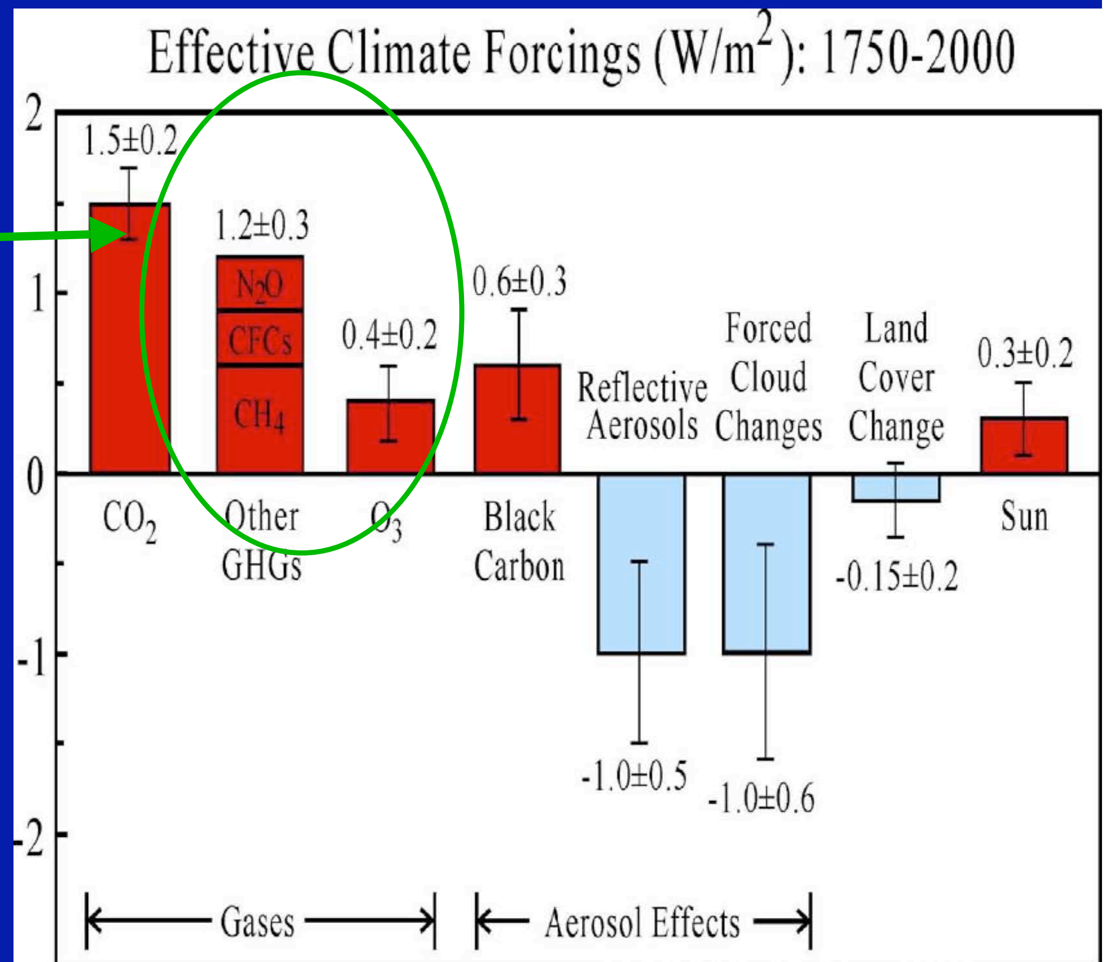
Outline

- Overview of GHG trends
  - Focus on California emissions
- CALGEM Measurements
- Two Inverse Approaches
  - "Gas ratio" or "unknown:known"
  - "Formal Inverse": Optimize *a priori* emissions to match measurements using meteorological and Baysian statistical models
- Summary
- Further work

Climate Forcing Pre-Industrial - Present

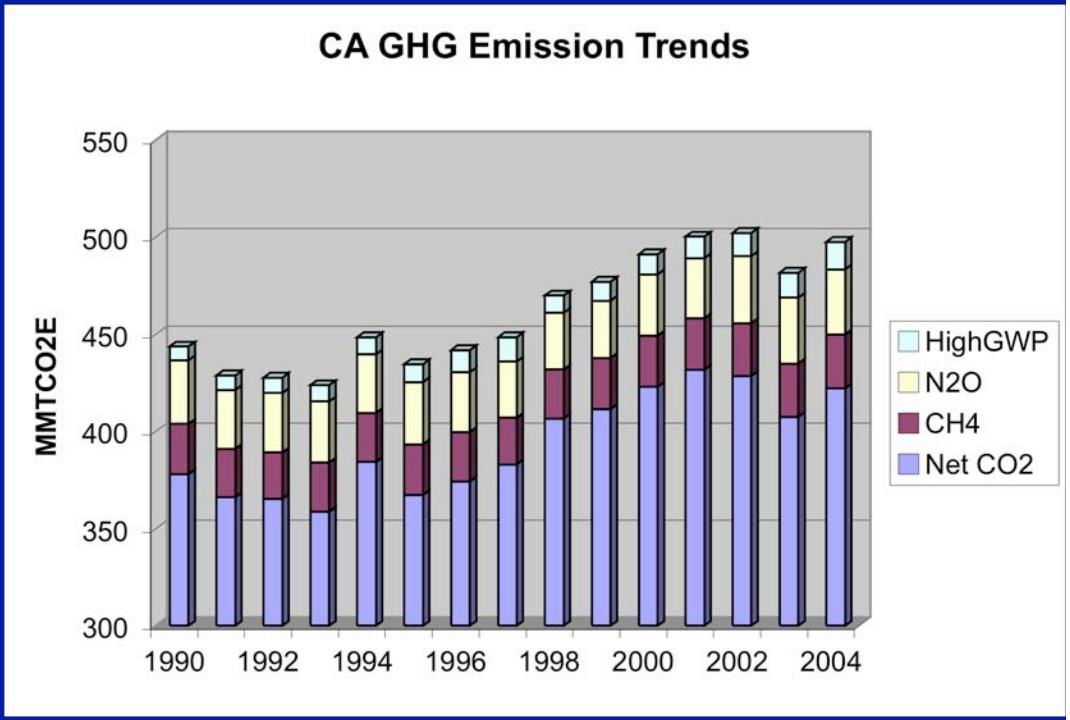
- Total non-CO_2 GHG forcing ~ equivalent to CO_2 forcing globally
- Non-CO_2 gases much stronger absorbers than CO_2 by mass
  - CH_4 (~ 20 x CO_2)
  - N_2O (~ 300 x CO_2)
  - High GWP (e.g., CFCs, HFCs, SF_6,)
    (~ 10^3 - 10^4x CO_2)
  - Tropospheric ozone



Hansen et al., 2005

California GHG Emission Trends

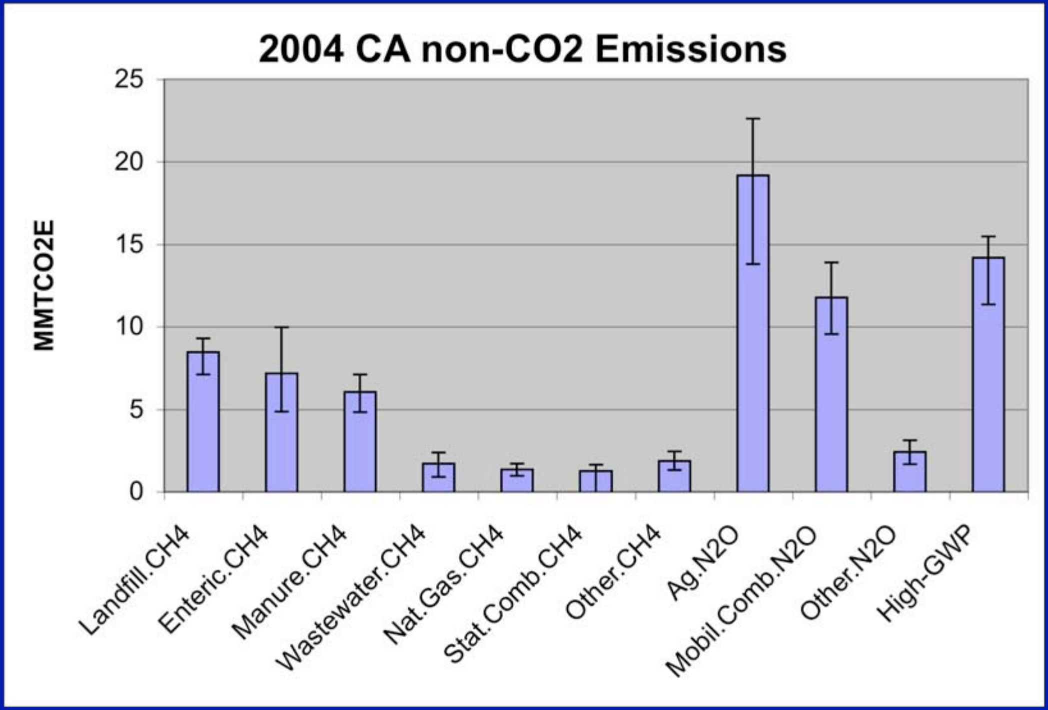
- CO_2 dominates GHG emissions
  - Controls must start with CO_2
- Non-CO_2 gases more uncertain
  - Opportunities for control exist in this sector
  - Quantifying current emissions important



CEC, 2006

California non-CO2 GHG Emissions

- Non-CO2 GHGs largely from biological sources
- Uncertainties are large
  - many sources not readily metered
  - Some gases not currently included (e.g. CFCs)
- Atmospheric approaches can provide independent constraints
- Evaluation of uncertainties is an essential challenge



CEC, 2006 ; USEPA, 2007

CALGEM Measurement Sites

Sutro Tower (232 m agl)
Oceanic + urban

Walnut Grove (483 m agl)
Valley + Bay Area

Instrumentation

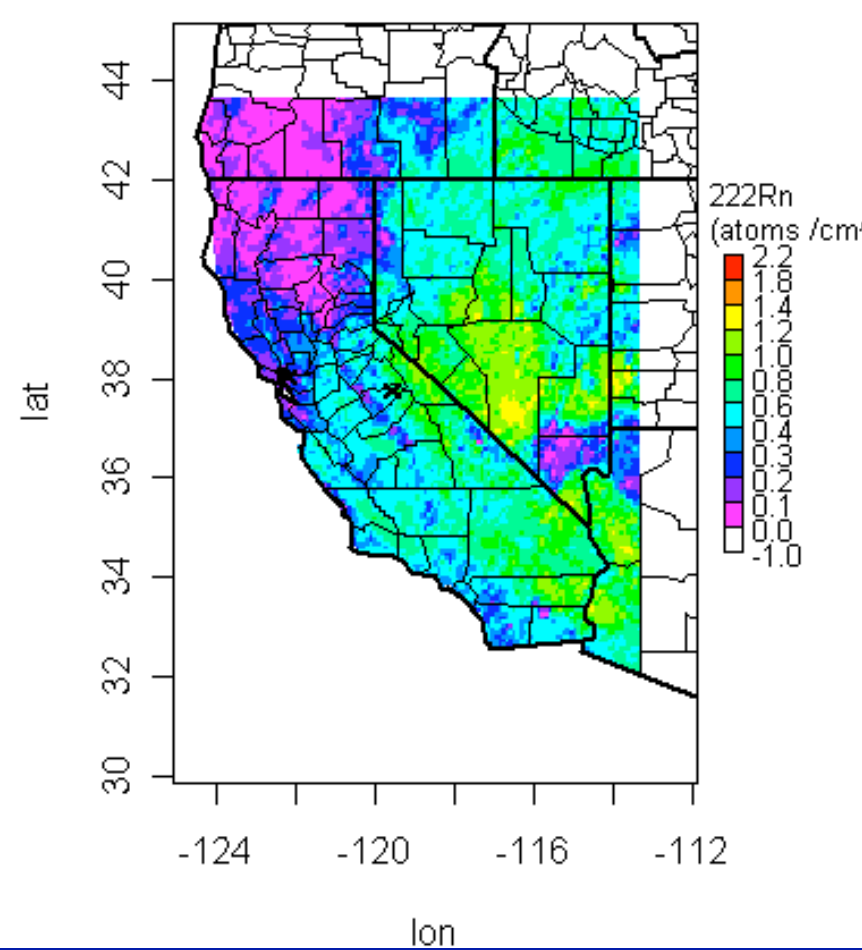
- Both Sites: 12 Flask System
  - Twice daily samples
  - CO_2,CH_4,N_2O,CO
  - high GWP gases
  - $^{13}CO_2$, $^{13}CH_4$, CDH

- Walnut Grove:
  - CH_4/CO_2 analyzer- 3min
  - CO_2/CO rack – 3 min
  - ^{222}Rn monitor – 30 min
  - $^{14}CO_2$ (w/ LLNL)

Atmospheric Tracers

- ^{222}Radon from soils
  - Short half life (3.8 day) gives atmospheric contact with terrestrial systems
  - Emission rate depends on ^{238}U soil content, moisture
  - Need CA specific model calibration including soil moisture
- CO - combustion tracer
- Isotopes
  - $^{14}CO_2$ none in fossil fuel
  - ^{13}CO2 (Nat gas vs. gasoline)
  - $^{13}CH_4$, CDH_3 (landfills, vs. nat. gas)

Relative ^{222}Radon Flux

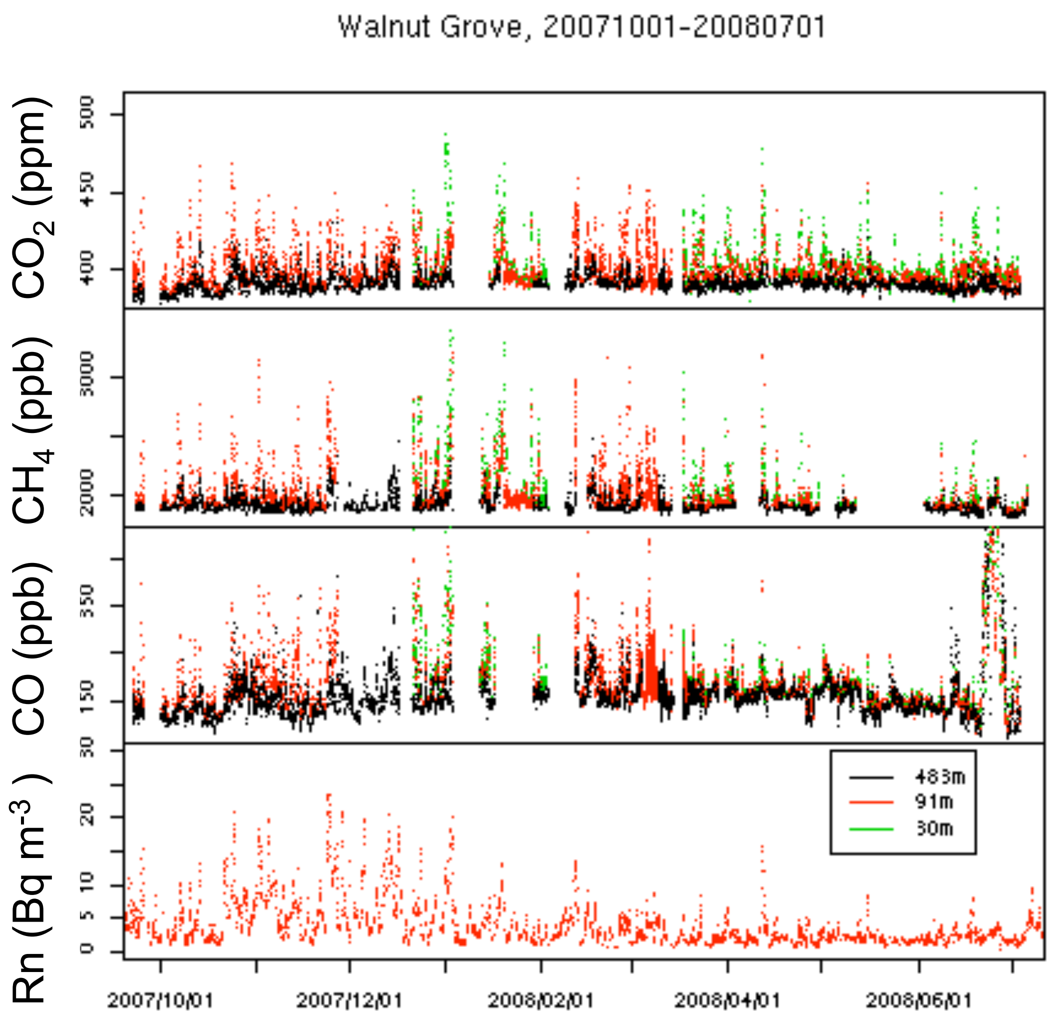


(Szegvary, 2006)

In-situ Measurements at Walnut Grove

First 9 months reveal:

- Elevated mixing ratios at 30, 91m indicate strong regional-local emissions
- Strong correlation of diurnal variations in CO_2, CH_4 and ^{222}Rn implicates variations in boundary layer
- Synoptic variations offer opportunity to extract emissions information
- 483 m mixing ratios generally near background levels at night (decoupled from surface)



Gas-Ratio Approach (1)
GHG emissions from ^{222}Rn Correlation

Mixing model for GHG flux:

$\langle F_x \rangle = \langle F_{Rn} \rangle * dC_x/dC_{Rn}$

(if $\langle F_{Rn} \rangle = 0.3$ atom $cm^{-2}\ s^{-1}$)

F_{CO2} ~ 35 t CO_2/ha/yr

F_{CH4} ~ 200 kg CH_4 /ha/yr

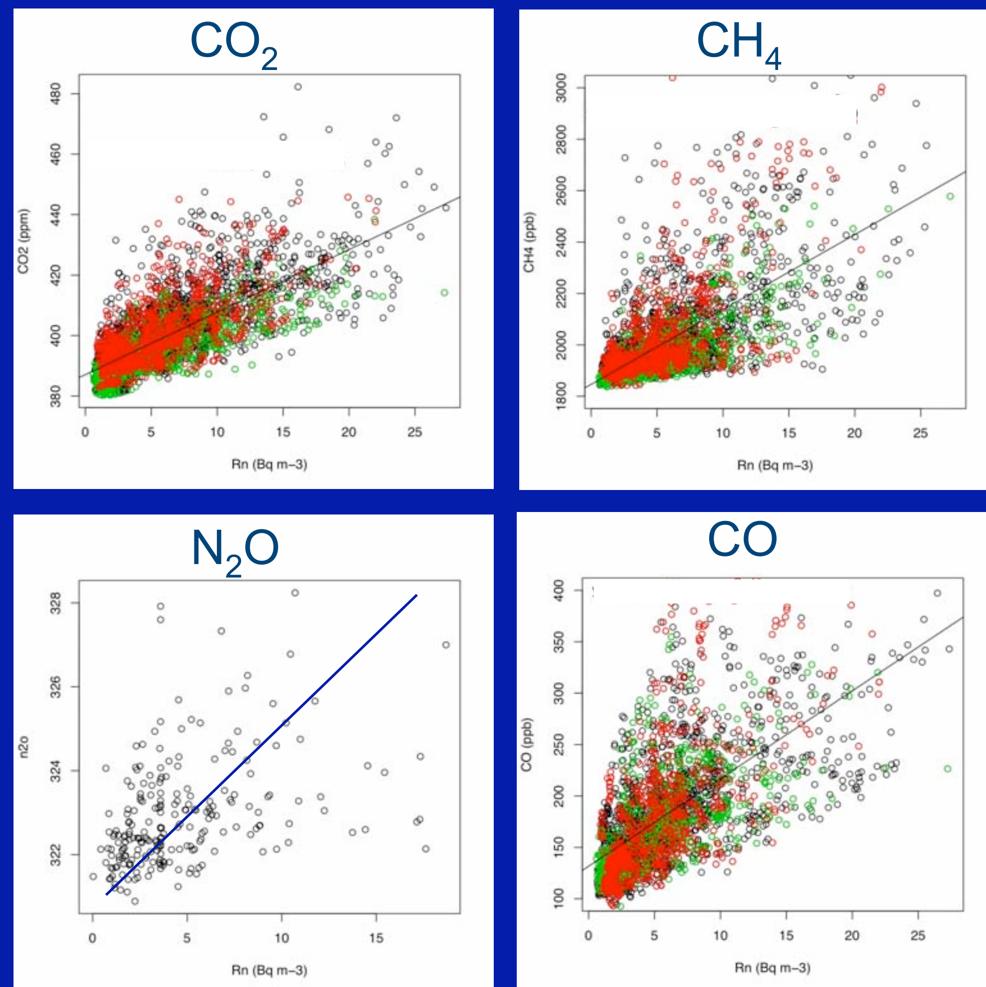
F_{N2O} ~ 5 kg N_2O/ha/yr

F_{CO} ~ 130 kg N_2O/ha/yr

note: slopes all estimated to < 10%

Next steps:

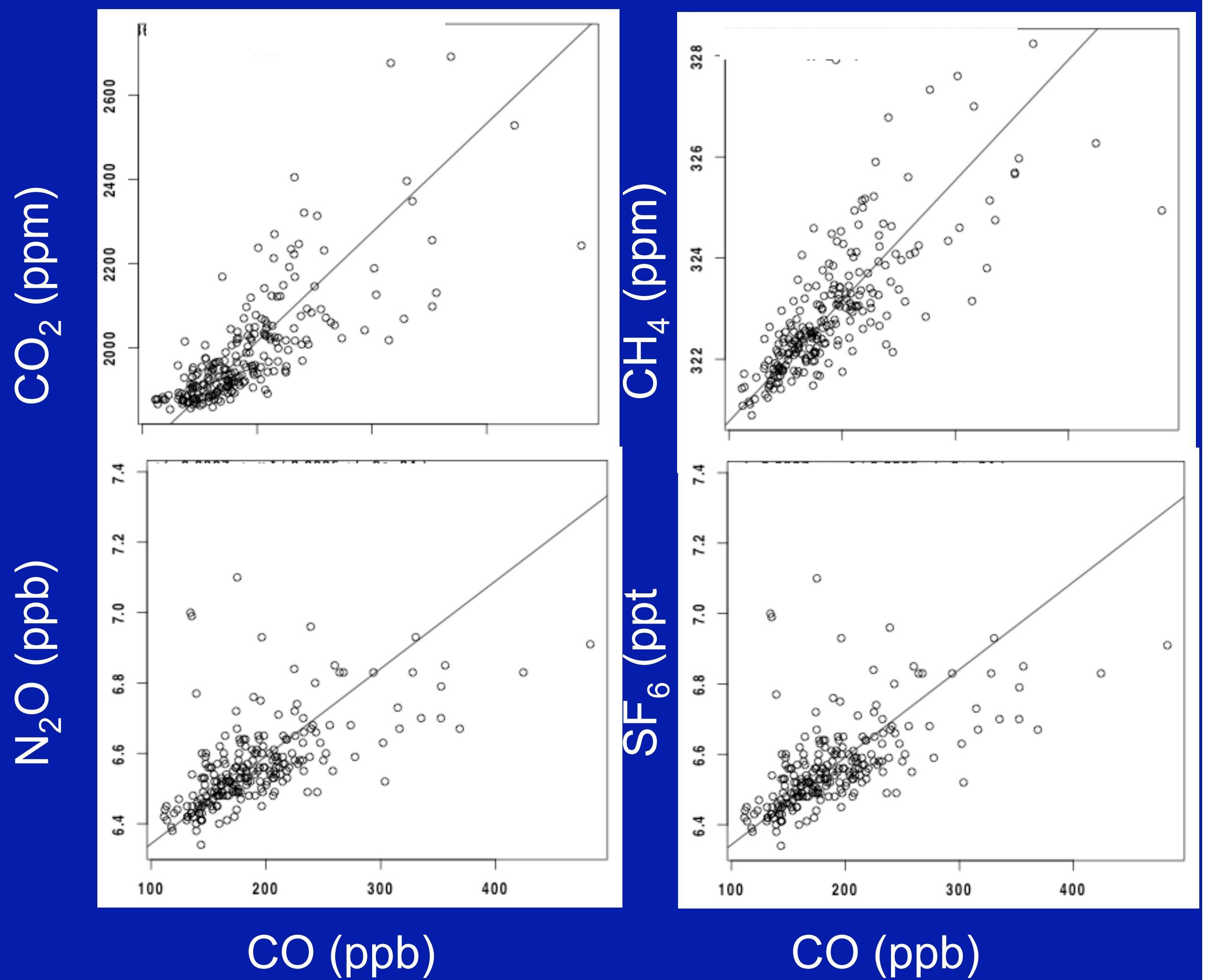
- Check Rn emissions
  - Trends might be determined if Rn emissions remain constant (Messager, 2008)
- Use CO as an alternate tracer



Rn (Bq m^{-3}) Rn (Bq m^{-3})

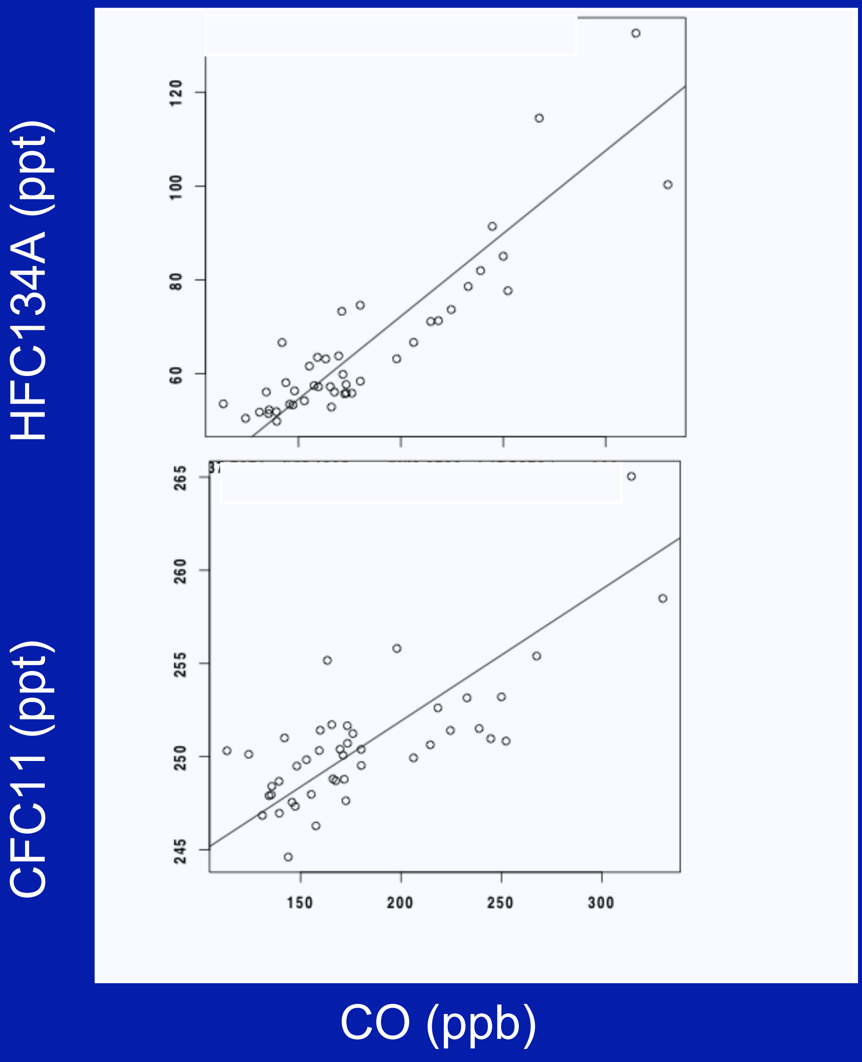
Gas-Ratio Approach (2)
GHG correlations with CO

- High correlations to CO yield accurate estimates of slope
- Need footprint weighted CO emissions for use in estimating GHG emissions



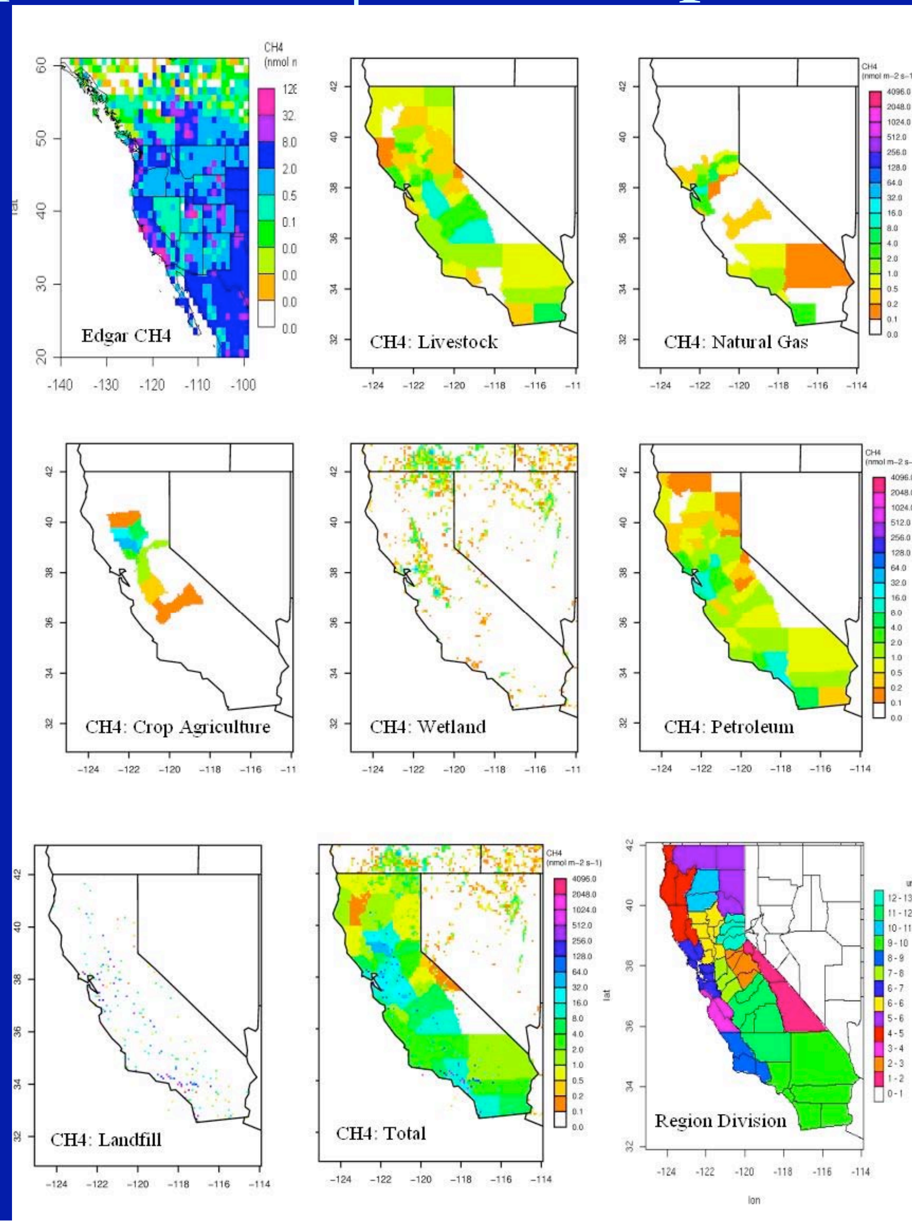
Gas-Ratio Approach (2) High-GWP Gas Emissions

- Good Rn (and CO) correlations obtained for several important high-GWP gases
- Applying Rn mixing model yields estimated emissions for 14 high-GWPs in central CA
- If high-GWP gas emissions similar in other populated areas then emissions are ~ 14 $MtCO_{2equiv}\ yr^{-1}$
- Find CFC11 and CFC12 emissions are also ~ 10 $MtCO_{2equiv}\ yr^{-1}$, similar to other high-GWP gases



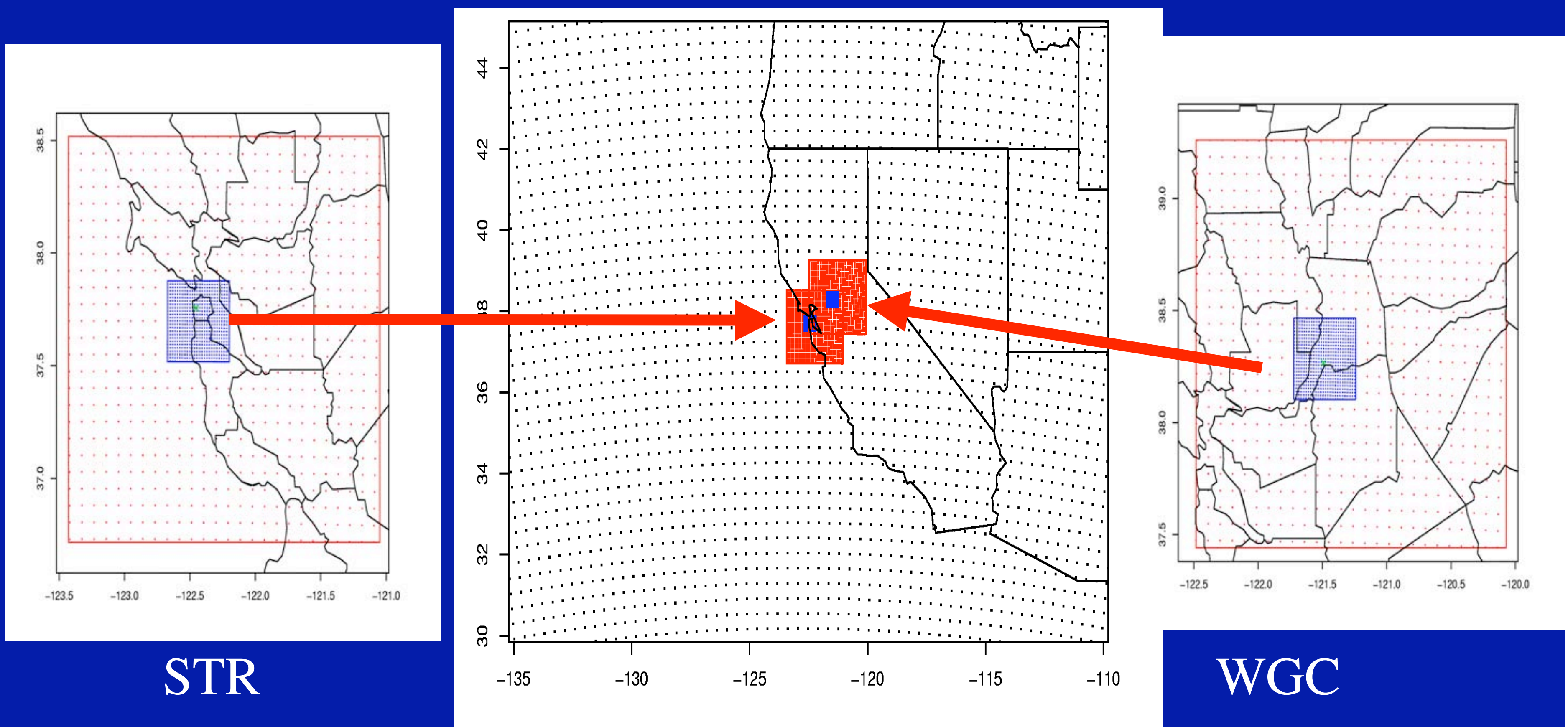
Formal Inverse (1) a priori CH_4 Flux Maps

- EDGAR3.2 (1x1degree)
- Landfill (point sources)
  - Landfill specific loading with substrate dependent residence time (EPA)
- Animal Ag. (county level)
  - USDA county level stocking
  - Dairy/meat emission factor
- Natural gas dist./use (county level)
  - County level facility/usage statistics (ARB)
- Wetlands (4 km)
  - NASA-CASA (Potter, 2006)
- Crop Agriculture (5 km)
  - County level DNDC (Salas et al., 2006)



Formal Inverse (2)
WRF Meteorology for Tower Sites

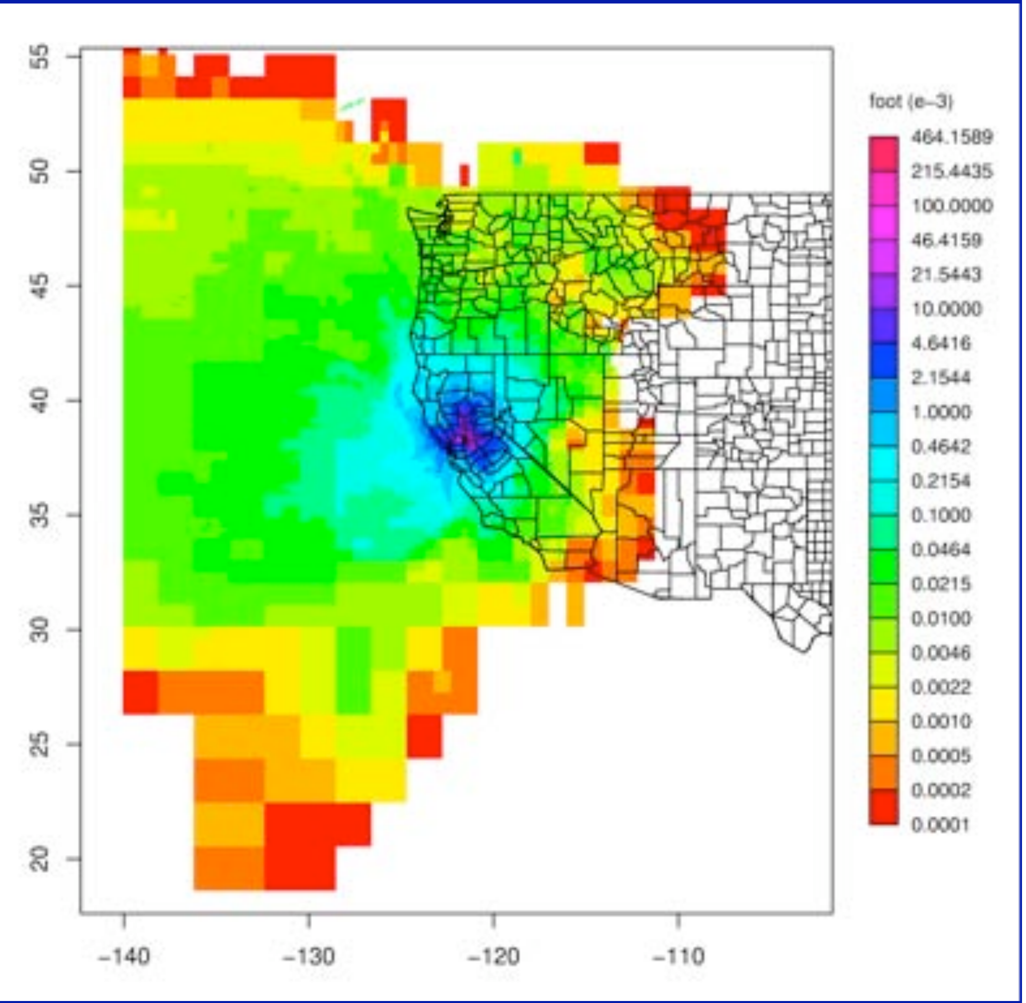
- Outer grid covers Western US at 40 km resolution
- Middle grids cover Bay Area and Sac. Valey at 8 km resolution
- Inner grids cover Sutro and Walnut Grove sites at 1.6 km resolution



Formal Inverse (3)
WRF-STILT Footprints for WGC Tower

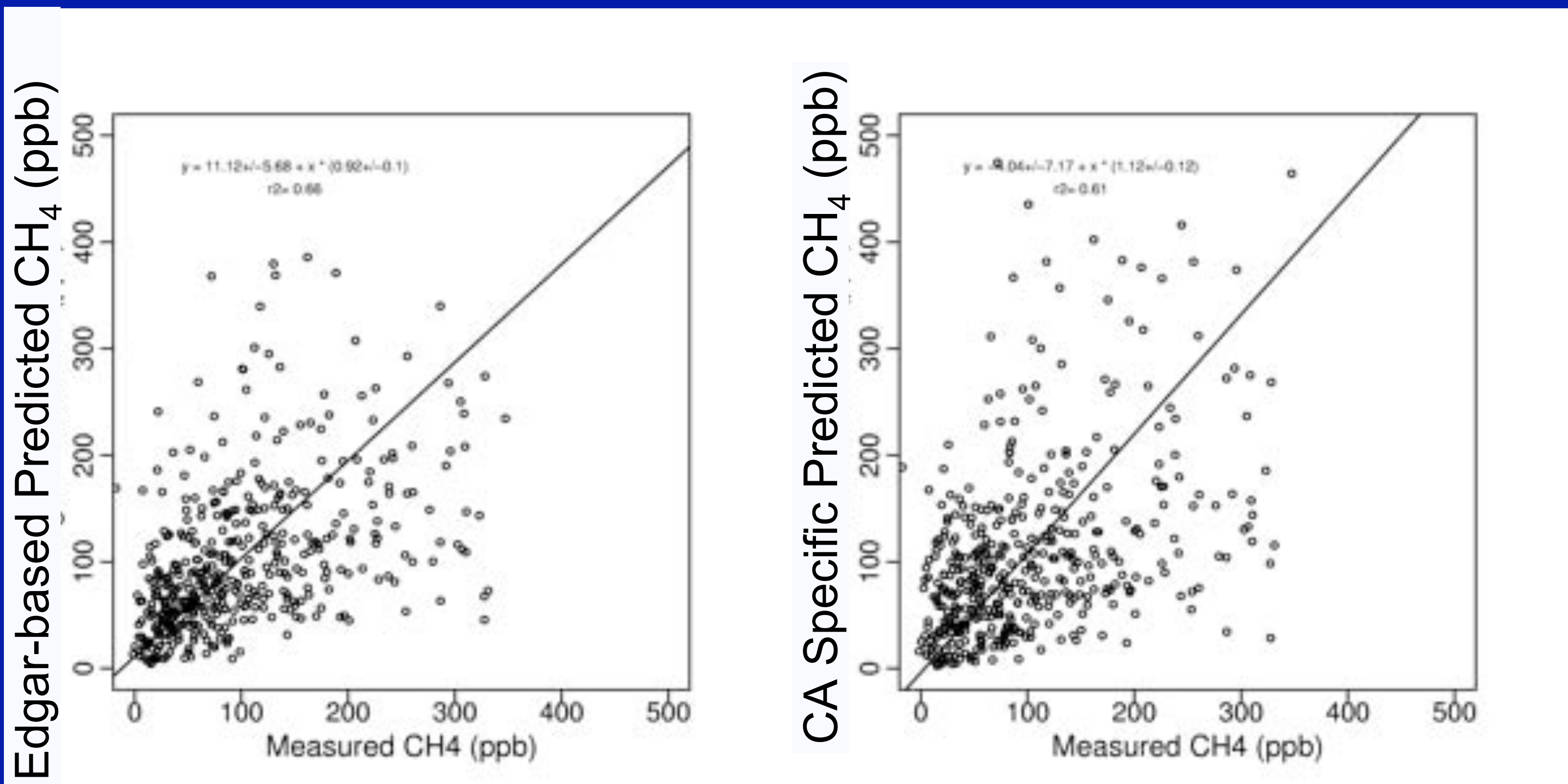
- Example of average footprint for Oct-Dec, 2007 (from hourly maps)
- Largest surface influences (purple) for Bay Area and Central Valley
- Use each hourly footprint maps to calculate predicted CH4 signal

$$CH_{4pred} = F_{CH4} * foot$$



Measured and Predicted CH_4 : Regression Analysis

- Edgar and CA specific emissions estimates produce predicted vs. measured signals with similar slopes (0.92 ± 0.1 and 1.12 ± 0.12 respectively)



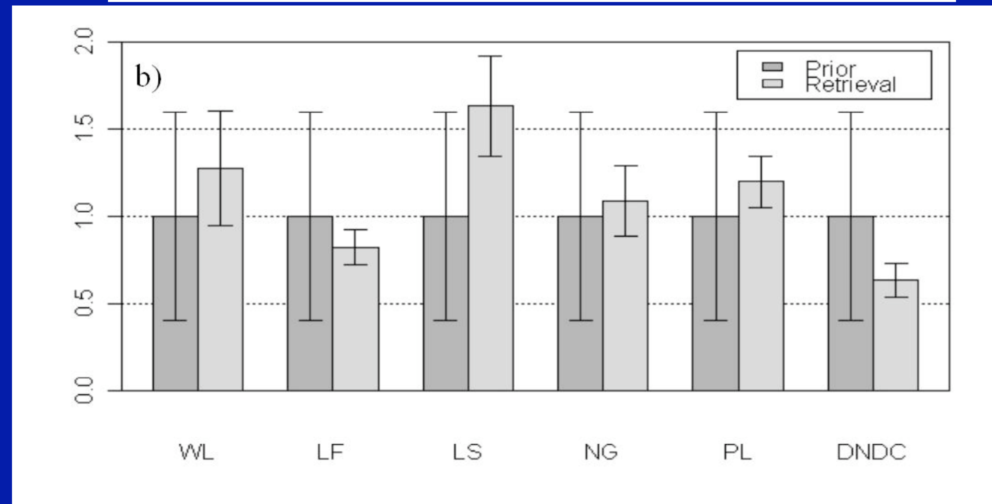
Formal Inverse (5): Posterior CH_4 Fluxes

• Estimate scaling factors for each emission source in Baysian approach
• *a priori* errors assigned at 30% for each source

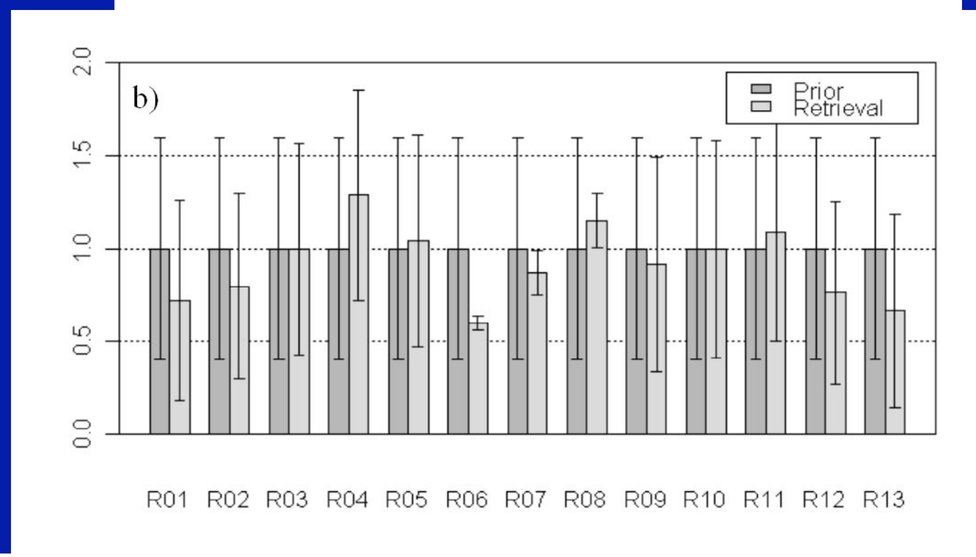
•Results:
1) Source analysis retrievals estimate landfill and crop emissions smaller (0.8 ± 0.05, 0.63 ± 0.05), and livestock emissions higher (1.6 ± 0.15)

2) Region analysis retrievals demonstrate that only regions near tower are constrained by measurements (reducing uncertainties) while distant regions are not

Source Analysis



Region Analysis



Summary

- Compliance with AB-32 requires verification of emissions reductions
- Atmospheric measurements provide independent and complementary test of inventories
- Non-CO_2 GHG particularly uncertain
- CALGEM measurements demonstrate that non-CO_2 GHG signals are readily measurable
- Gas-ratio emission estimates may constrain emissions but more work is needed
- Formal inverse approach combines data and model to refine *a priori* CH_4 emission estimates

Further Work

- Quantitatively assess inverse model uncertainties
  - Include profiler data to assess meteorological model errors
  - Compare/combine gas-ratio and inverse methods
  - Combine data from WGC, STR, aircraft flights in inverse
- Measure other GHGs and tracers:
  - CO_2: $^{14}CO2$ for combustion and fossil attribution
  - N_2O: Formal inverse model (DNDC prior + automobile, other)
- Combine data across activities with other groups
  - CARB CO inventory as alternate tracer
  - ARCTAS measurements at WGC
  - Work toward multi-site data analysis system for CALNEX2010